

PROSPECTS FOR THE LENSING OF SUPERNOVAE

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Observations of high redshift type Ia supernovae (SNe) will enable us to probe the structure of galaxy halos and the composition of dark matter. The future prospects for this field are briefly discussed here. First the ability of SN observations to differentiate between dark matter made of macroscopic compact objects and dark matter made of microscopic particles is reviewed. Then a new method for probing the structure of galaxy halos and galaxy cluster halos is described. This method utilizes the correlations between foreground galaxy light and supernova brightnesses to substantially decrease possible systematic errors. The technique may be particularly useful for measuring the size of dark matter halos, a measurement to which the galaxy–galaxy lensing is not well suited, and the level of substructure in galaxy halos, a problematic prediction of the cold dark matter model. The required observations of hundreds of SNe at $z \sim 1$ are already being proposed for the purposes of cosmological parameter estimation.

1 Introduction

There are still many outstanding problems in the fields of structure formation and dark matter which gravitational lensing has not yet been able to address. Outside of the visible extent of galaxies not a great deal is known about the distribution of dark matter (DM) on scales smaller than galaxy clusters. Galaxy–galaxy lensing has put some constraints on the mass of galaxy halos, but their size scale and the degree to which they are smooth mass distributions or collections of subclumps are not well determined.^{1,2,3,4,5} Even the concept of galaxy halos, with a single galaxy within each of them and well defined sizes, may not be correct. Nor is it clear how the observable properties of galaxies relate to the DM distribution around them. Recently dark matter simulations have revealed several problems with the cold dark matter (CDM) model. One of these is that CDM predicts a large amount of small scale structure within halos which is unaccounted for in the observed distribution of light.⁶ In addition, the composition of DM

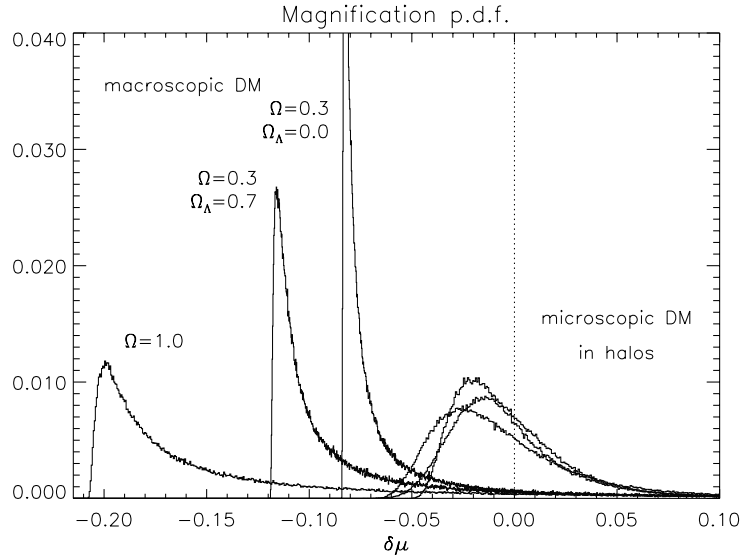


Figure 1: These are the magnification probability distributions for point sources in several models. The three distributions peaking on the left are for DM composed entirely of macroscopic compact objects. The background cosmologies are listed. The more centrally concentrated distributions on the right are for microscopic DM concentrated into galaxy halos. These distributions are functions of both the background cosmology and the halo model. Changing the halo model makes relatively little difference if the fraction of mass in halos is kept fixed.

is still a mystery: it could be large compact objects like black holes or it could be microscopic particles like WIMPs. Even with primordial nucleosynthesis bounds roughly half the baryons are in some form that has yet to be directly detected – conceivably in condensed objects. I will describe here how the gravitational lensing of type Ia SNe can help to answer some of these questions. Lack of space dictates that this only be an outline and that the reader be referred to more detailed papers.

High redshift type Ia SNe have recently been used by two collaborations to measure cosmological parameters.^{7,8} These measurements and the proposed application of Ia’s to gravitational lensing are made possible by the discovery of a tight correlation between the light curve shapes and peak luminosities of these SNe.^{9,10} The measured standard deviation of corrected peak luminosities in local SNe is now $\lesssim 0.12$ mag. The successes of these collaborations have inspired plans for more aggressive, larger searches for high redshift SNe in the near future. The volume and quality of data is likely to increase dramatically. Besides constraining Ω_m and Ω_Λ these data, amongst other things, would be ideal for gravitational lensing studies.

In the next section I will discuss how SNe can be used to determine if dark matter is composed of macroscopic compact objects and in section 3 the case of DM composed of microscopic particles is taken up.

2 Lensing by macroscopic compact objects

Some magnification probability distributions for a point source at $z = 1$ are plotted in figure 1. The means of all these distributions are zero which corresponds to the usual Friedman-Robertson-Walker (FRW) luminosity distance. When DM is made entirely of macroscopic compact objects the distribution peaks well below the mean making most SNe under-luminous. The peak of the distribution is just slightly brighter than the solution corresponding to the empty beam or Dyer–Roeder luminosity distance¹¹. This is the formal solution of Sachs optical scalar equations¹² for a beam that passes through only empty space (no Ricci focusing) and has no

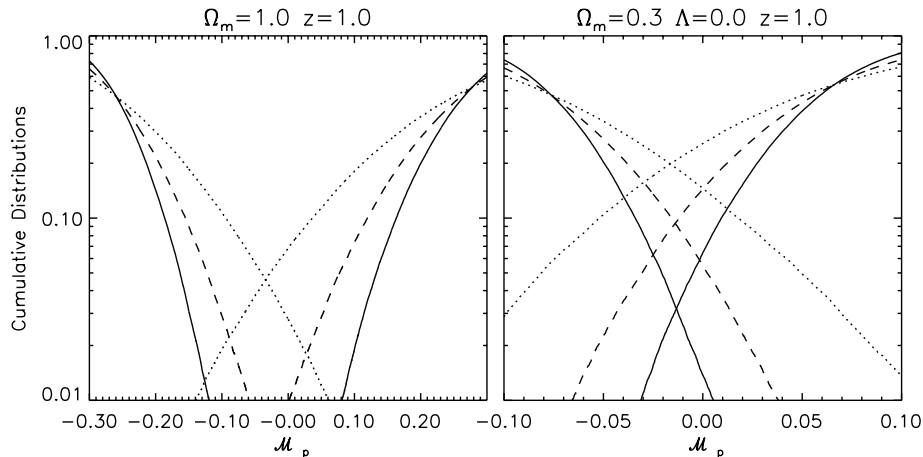


Figure 2: The cumulative distributions of \mathcal{M}_p for different models and different numbers of observed SNe. The dotted curves are for 21 observed SNe, the dashed for 51 and the solid for 101. The pairs of like curves represent the cases of macroscopic and microscopic DM. The distributions for the cases of macroscopic DM rise to the right while if DM is microscopic \mathcal{M}_p is expected to be smaller. The overlap of these distributions is small signifying that DM candidates could be distinguished using this statistic. For a flat cosmological model the constraints are stronger than for the $\Lambda = 0$ model with the same Ω_m . The variance in SN luminosities is $\sigma_{sn} = 0.16$ mag.

shear on it. The long, high magnification tail to these distributions correspond to rare cases where a DM object is very close to the line of sight. At $z < 2$ it is unlikely that multiple lens lie so close to the line of sight that their lensing effects become nonlinearly coupled which significantly simplifies calculations.

The distributions for microscopic DM shown in figure 1 assume that the DM is clustered into halos surrounding galaxies. The exact form of the clustering is not important for this section. As the figure shows, these distributions are significantly more centrally concentrated about the FRW solution. With macroscopic DM the magnification is dominated by Ricci focusing – the isotropic expansion or contraction of the image caused by matter within the beam – while in the macroscopic case (with true point sources) it is entirely due to shear caused by matter outside of the beam. This is the essential difference between the two cases and why they can be differentiated using SNe observations.

To differentiate between DM candidates we construct the statistic

$$\mathcal{M}_p \equiv \frac{1}{N_{sn}} \ln \left[\frac{P(\{\delta\mu\} | \text{macro DM, noise})}{P(\{\delta\mu\} | \text{micro DM, noise})} \right]. \quad (1)$$

where the P 's are the probability of getting the N_{sn} observed SN magnifications given that DM is of the specified type and given the expected noise. \mathcal{M}_p is close to normally distributed for a modest number of SNe. Some example distributions of \mathcal{M}_p are plotted in figure 2. If DM is microscopic \mathcal{M}_p is expected to be small while if DM is macroscopic it will be large. Figure 2 shows that with 100 SNe at $z \sim 1$ one is unlikely to confuse the two cases.

This technique works for DM objects with masses $\gtrsim 10^{-3} M_\odot$. For smaller masses it is probable that the expanding SN photosphere will make the magnification time dependent which is an interesting subject in itself. For more details on differentiating DM candidates see Metcalf & Silk.¹³

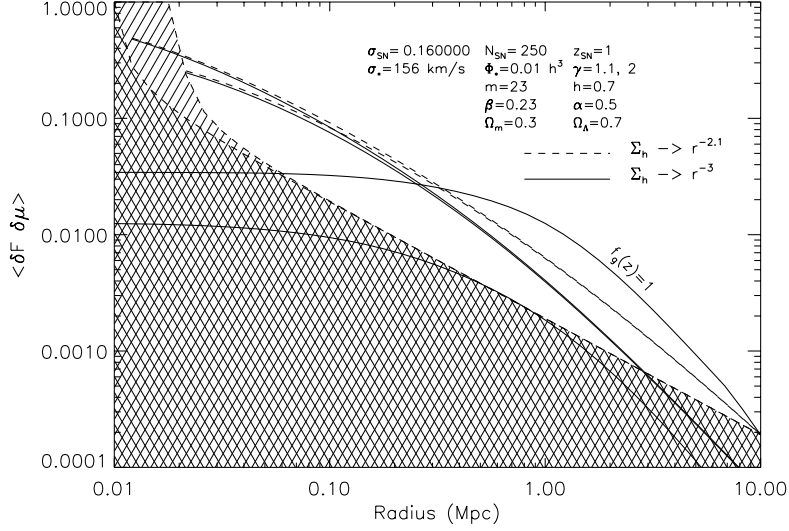


Figure 3: The expected correlation between foreground light and SN luminosity. There are two contributions plotted separately here. The first contribution is from *galactic halos* which are presumed to surround every galaxy and have properties which are related to the observed properties of their resident galaxy. In addition there is a contribution from *extragalactic halos* or galaxy clusters which contain multiple galactic halos and additional matter within them. The total correlation is the sum of the two components. The galactic halo curves are the steeper ones starting in the upper left corner. Two different models which differ in the logarithmic slope of the surface density at large galactic radii are shown. At small galactic radii the galactic halos approach the form of singular isothermal spheres. For each model two inner cutoffs are considered – $R_{min} = 10, 20$ kpc. To avoid obscuration all SNe within R_{min} of any galaxy are excluded. The two curves that flatten out on the left are the contributions from extragalactic halos in the CDM model. These halos have Navarro, Frenk and White profiles. The one marked $f_g(z) = 1$ represents the case where only SNe behind $M > 10^{14} M_\odot$ clusters are selected. The crisscrossed region represents the noise contributed by uncertainties in SN peak luminosities ($\sigma_{sn} = 0.16$ mag) and shot noise in the foreground galaxy counts for the case of 250 observed SNe. The signal to noise ratio at $R = 200$ kpc is $\simeq 4\sqrt{N_{sn}/250}$. The limiting magnitude of foreground galaxies is $m = 23$.

3 Correlations between light and magnification

When the DM is made of microscopic particles it can be treated as a transparent, massive fluid clumped into structures that are much larger than the beam size. Because of lensing the variance of SN brightnesses will increase with redshift¹⁴ which introduces noise into the cosmological parameter estimates. The increases in variance is not the best way of detecting the lensing however. Using the correlation between foreground light and SN brightness reduces possible systematic errors associated with the evolution of the SN population and makes the measurement more directly sensitive to the mass and size scale of dark matter halos.

Lets define the weighted foreground flux for each SN as

$$\mathcal{F} = \sum_{y_i < R} w(z_i, z_s) f_i \quad (2)$$

where f_i the observed flux from the i th galaxy and y_i is its distance (angular or proper) from the line of sight to the SN. The weight function depends on the galaxy and SN redshifts. Figure 3 shows the expected correlation of \mathcal{F} with SN brightness, $\langle \delta \mathcal{F} \delta b \rangle$, for a SN at $z_s = 1$. This quantity is proportional to the average surface density within distance R of a galaxy.

By measuring this correlation the size scale of galactic halos could be constrained significantly better than with galaxy–galaxy lensing using a much larger data set. This is a result of the magnification being a steeper function of galactic radius than shear when the density profile is

steeper than isothermal. In addition, by selecting or searching for SNe behind galaxy clusters the structure of clusters and the smaller halos within them can be probed. For instance the tidal truncation of galactic halos could be investigated. Higher order correlations can also be used to look for substructure in galaxy halos. This subject is treated more thoroughly in a complete paper by the author.¹⁵

4 Discussion

The number of high redshift SNe required for the studies proposed here are well within the projected numbers for future SN searches – the VISTA telescope is expected to find hundreds at $z \gtrsim 1$ ^a and the proposed SNAPSAT satellite could find thousands up to $z \simeq 1.7$ ^b. The errors assumed in this paper are quite conservative compared to those expected for satellite observations. The future looks bright for this new field in gravitational lensing.

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^ahome page: <http://www-star.qmw.ac.uk/~jpe/vista/>

^bhome page: <http://snap.lbl.gov/proposal/>